



# Laboratory Techniques: Computer simulation of human movement

---

**Dr. Daniel Häufle** [daniel.haeufle@uni-tuebingen.de](mailto:daniel.haeufle@uni-tuebingen.de)

## Multi-Level Modeling in Motor Control and Rehabilitation Robotics

Hertie Institute for Clinical Brain Research

Eberhard-Karls Universität Tübingen



**Hertie-Institut**  
für klinische Hirnforschung

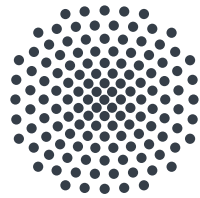
## Biomechanics and Biorobotics

Stuttgart Centre for Simulation Sciences

University of Stuttgart



# Collaboration



Universität Stuttgart

Syn  
Schmitt  
2B

**SimTech**  
Cluster of Excellence

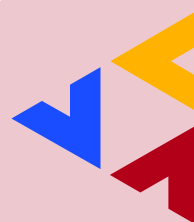
MoCoM

**CIN**  
Werner Reichardt  
Centrum für Integrative  
Neurowissenschaften

Comp  
Sens



**Hertie Institute**  
for Clinical Brain Research



Eberhard-Karls-Universität  
**UKT**  
Universitätsklinikum Tübingen

EBERHARD KARLS  
**UNIVERSITÄT  
TÜBINGEN**



# Cases

---

# Implants

---



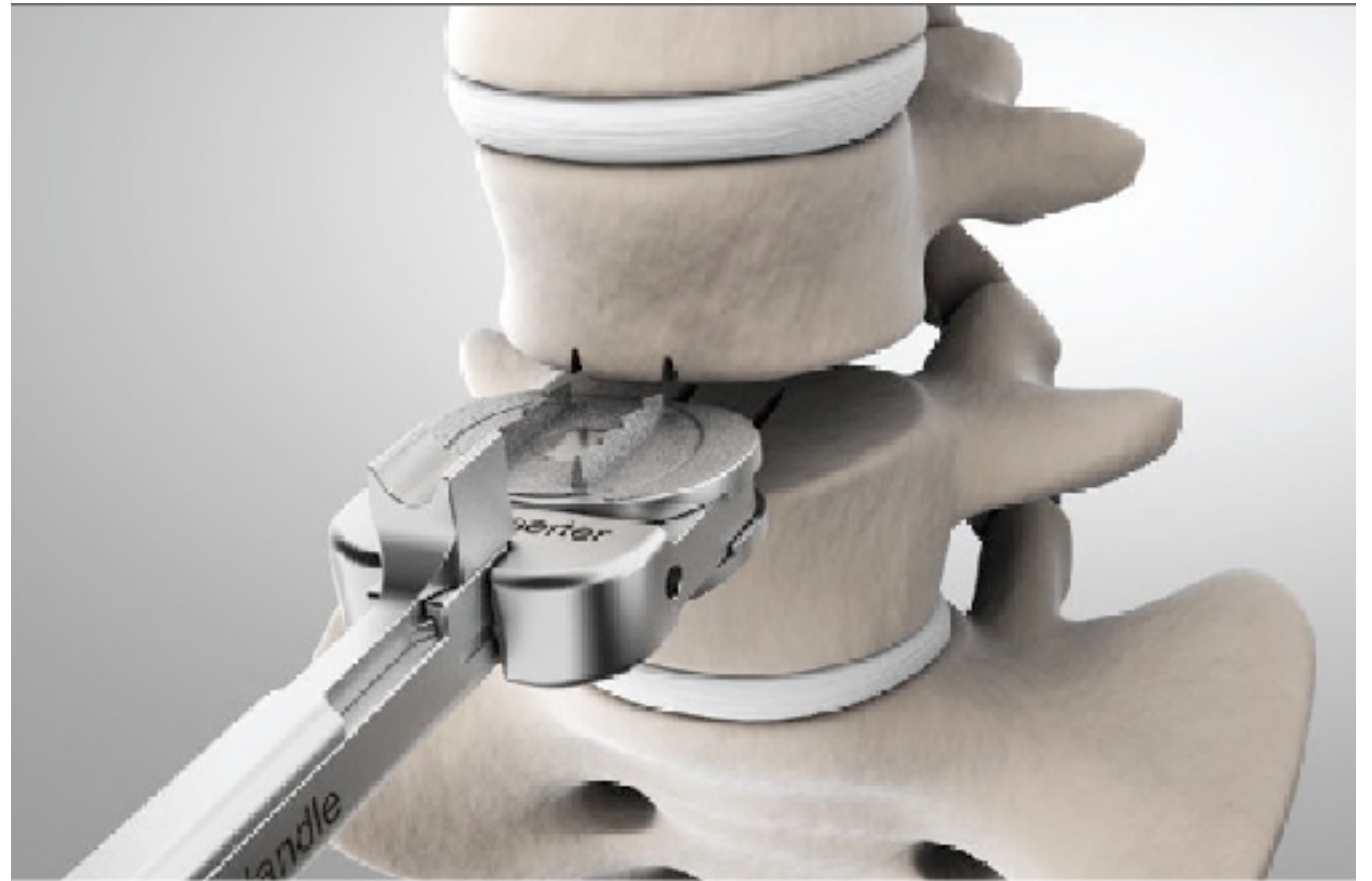
[http://www.qmed.com/sites/default/files/ck\\_images/biomet\\_hip\\_implant.jpg](http://www.qmed.com/sites/default/files/ck_images/biomet_hip_implant.jpg)

<http://www.osmifw.com/wp-content/uploads/2015/11/knee-replacement-x-ray.jpg>



# Intervertebral disks (IVD)

---



<https://www.joint-surgeon.com/orthopedic-joint-surgeon/artificial-spinal-disc/lumbar-disc-prosthesis-implantation-surgery.jpg>

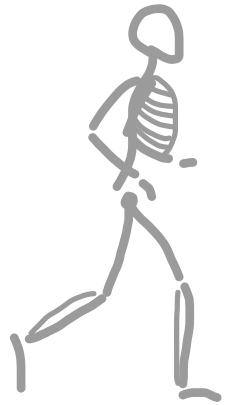
<http://sherwoodspinalcare.com/wp-content/uploads/2015/09/Spine.jpg>

**Problem:**  
**How to determine  
internal forces and  
loads?**

logosj

# Forces in the human body

---



Bones



Tissue



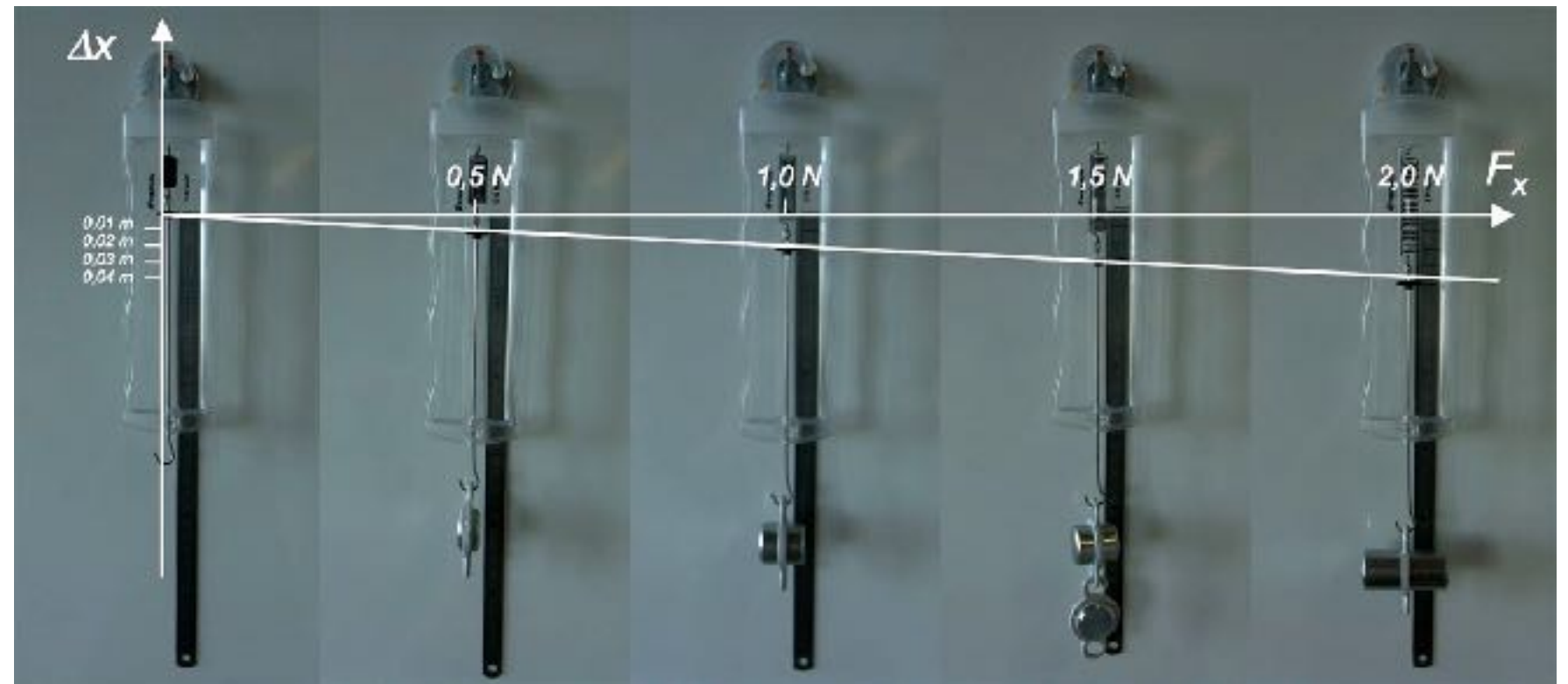
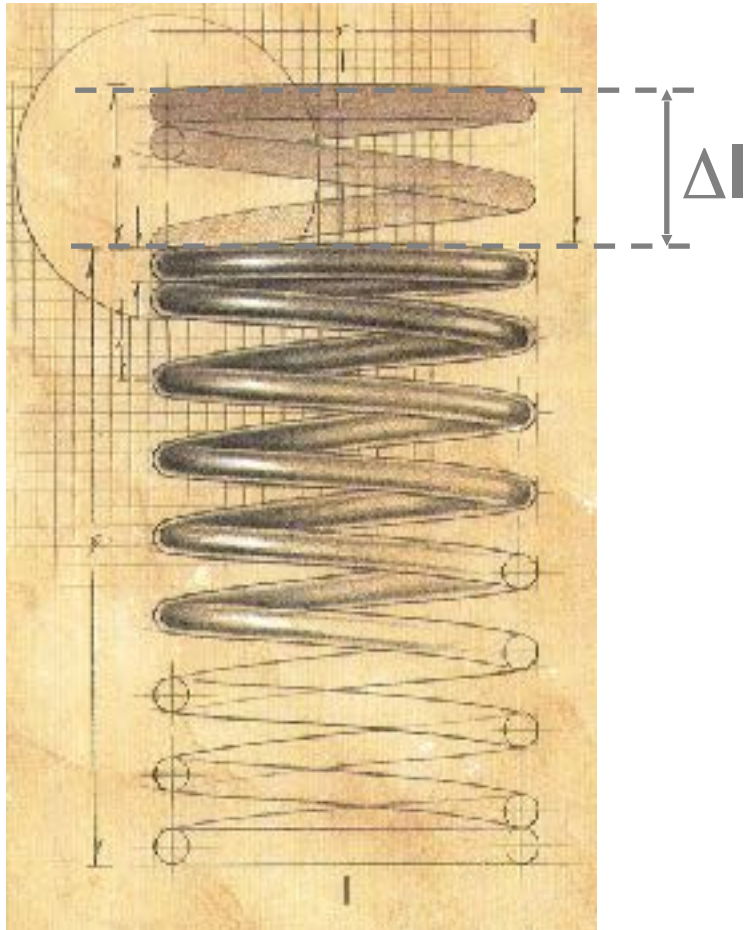
Muscle

# Newton's laws

---

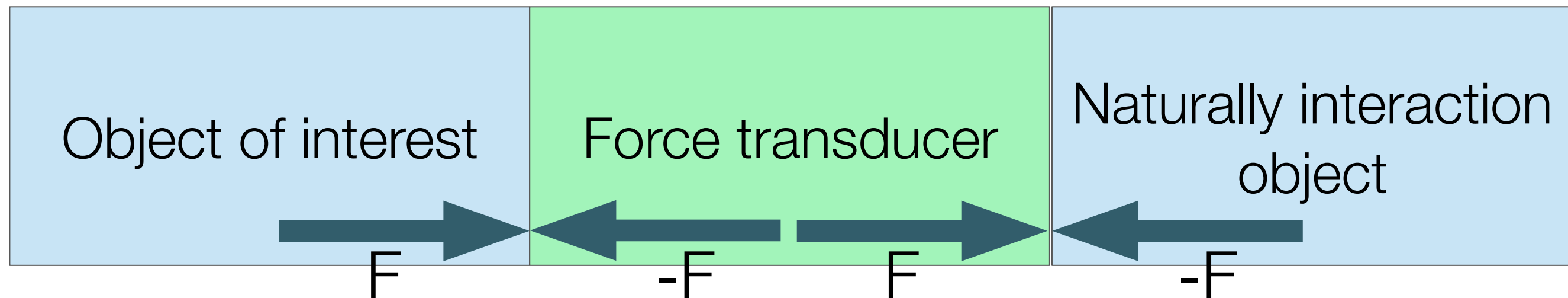
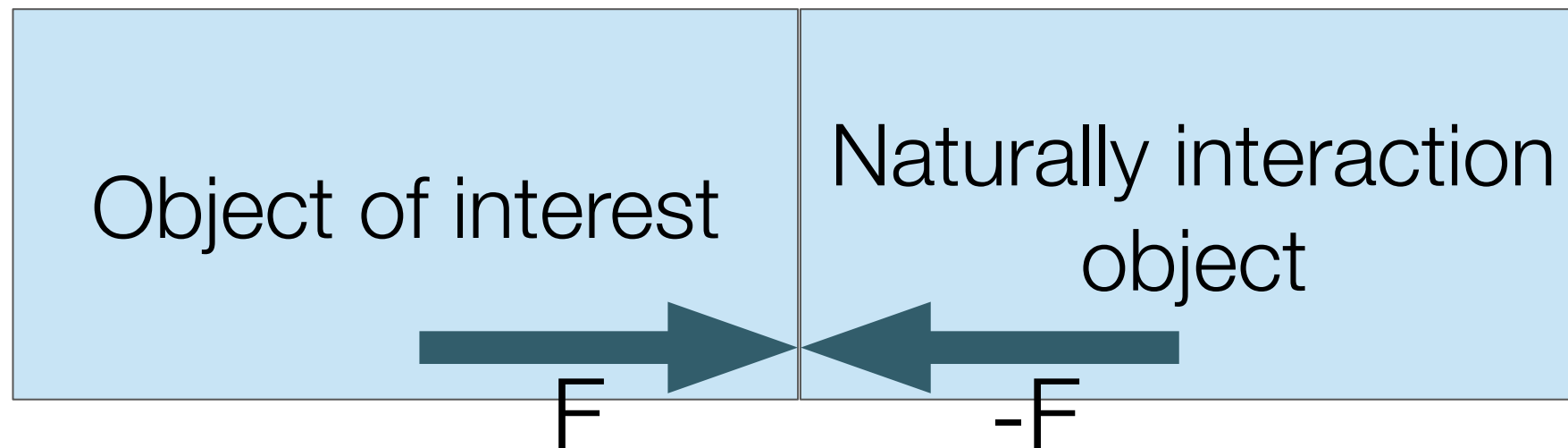
# How to measure force: first approach

---



# How to measure force

---



# Measure force in a tendon: Buckle force transducer

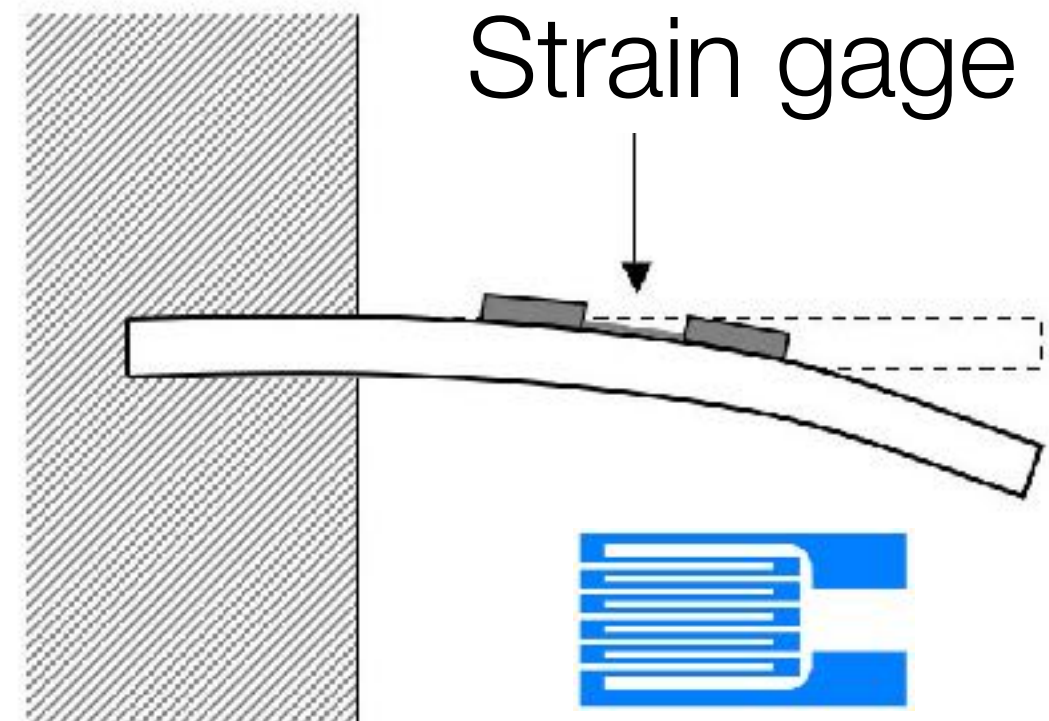
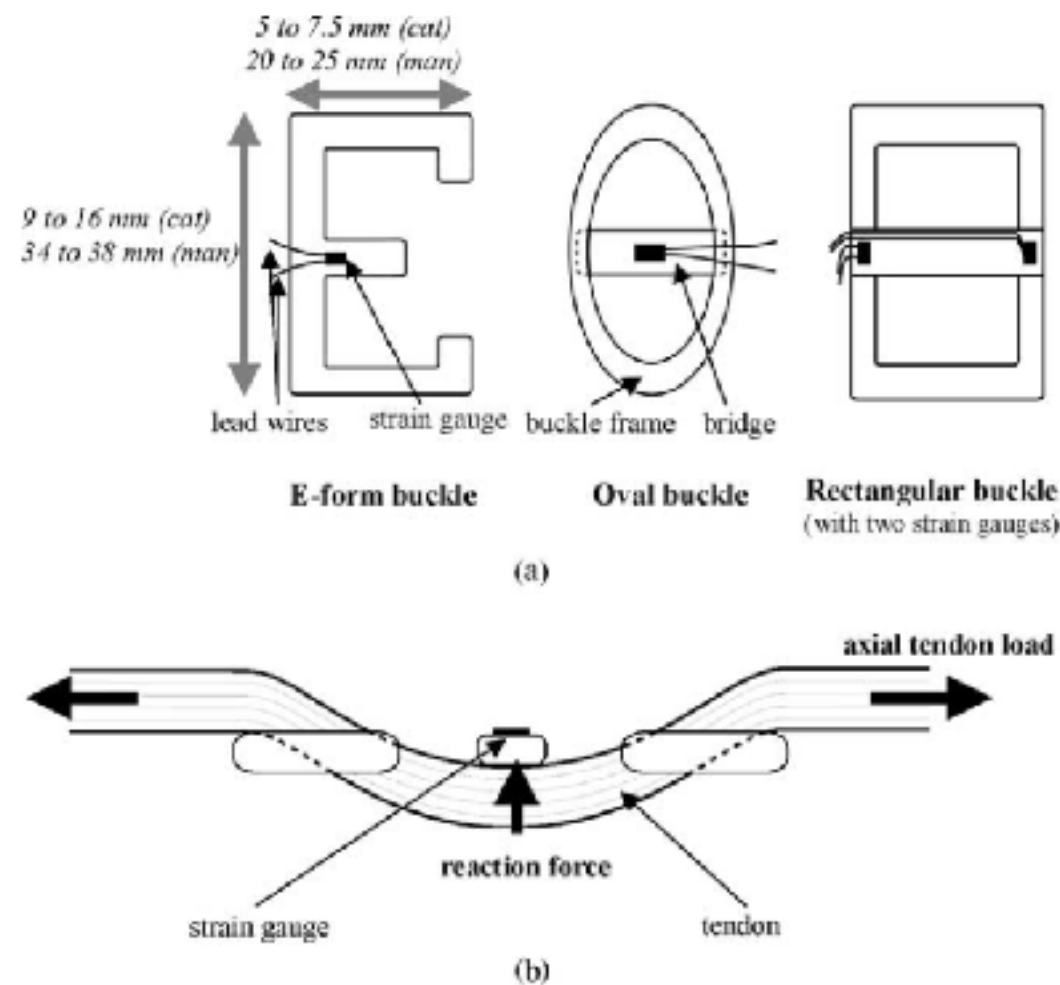
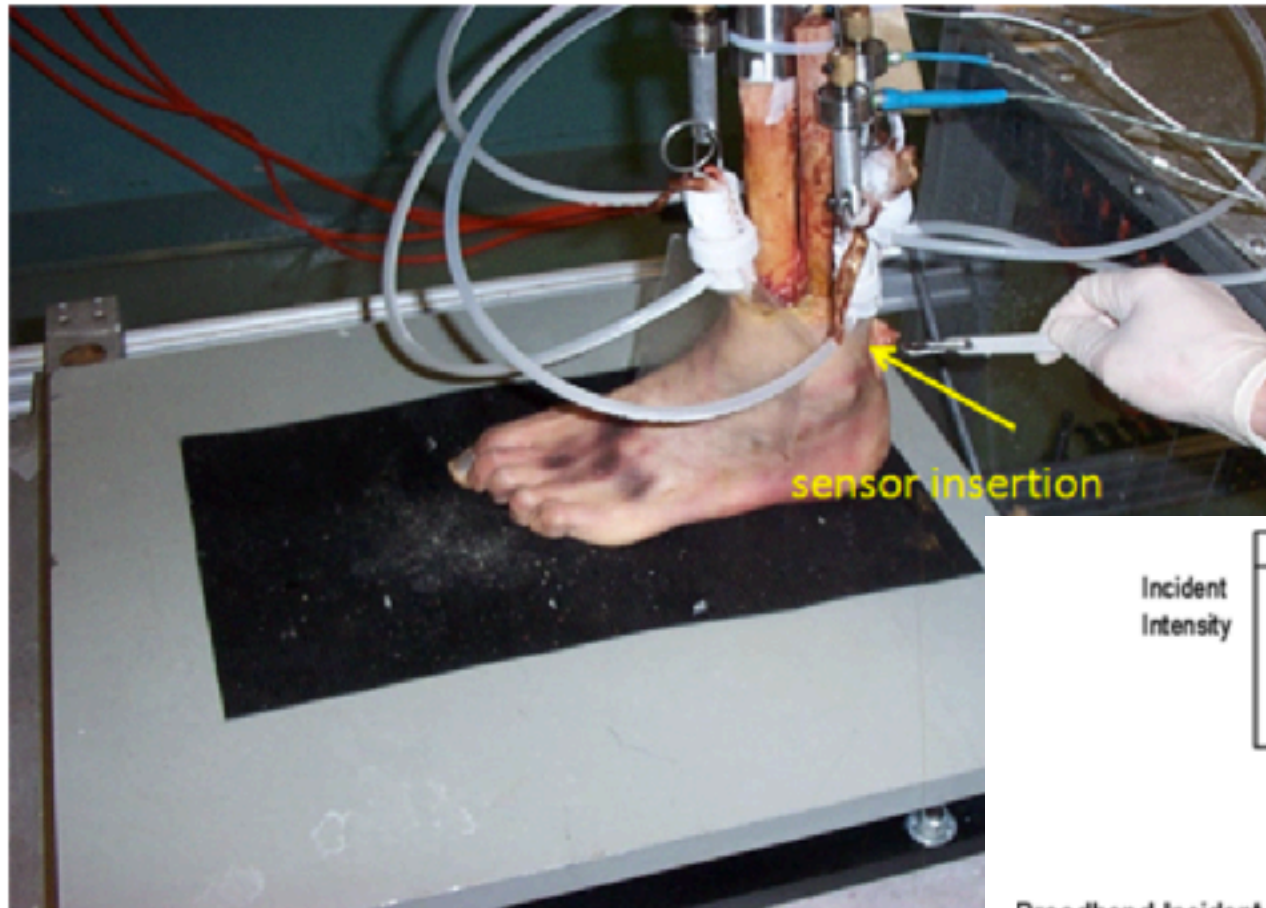


Fig. 2. Schematic diagram of the buckle transducer (Keegan et al., 1991, 1992; Roberts et al., 1994; Stone et al., 1983). (a) Schematic view and dimensions of the buckle transducer (top view of the transducer). (b) Position of the transducer within the tendon or the ligament (side view of the transducer).

# Optical fibre in the tendon



Behrmann et al. BioMedical Engineering OnLine 2012, 11:77 <http://www.biomedical-engineering-online.com/content/11/1/77>

16 The Dynamic Gate Simulator, CELOS, Penn State University.

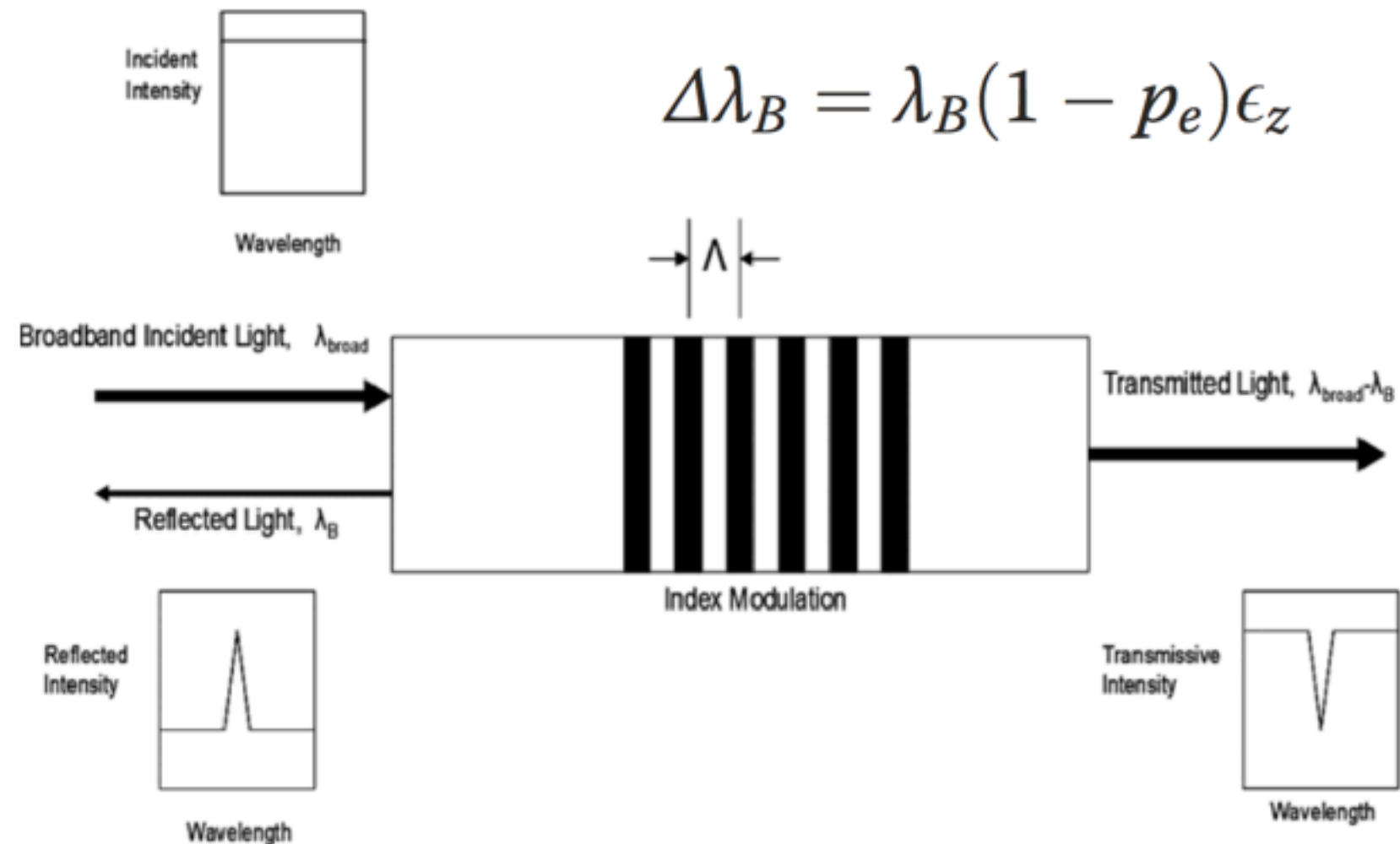


Figure 2 A fiber Bragg grating structure illuminated by broadband light.

# Measure pressure in IVD: pressure transducer

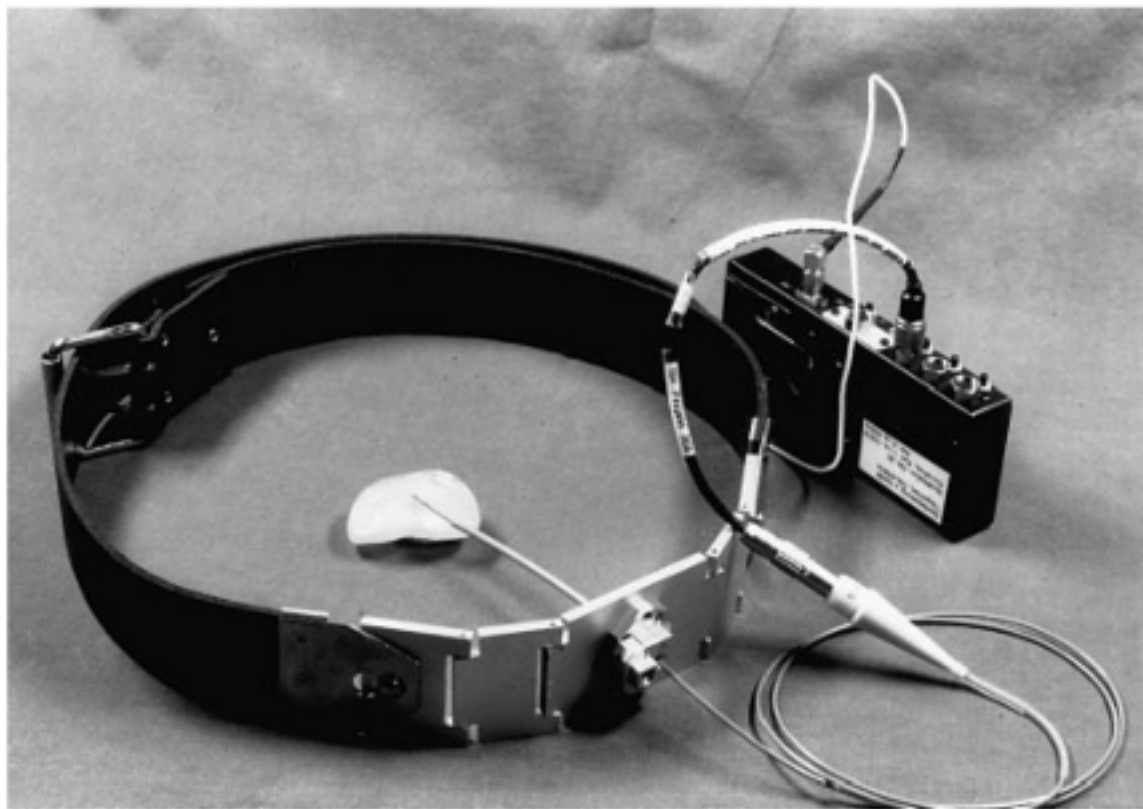


Figure 2. Spatial relation of implanted transducer, intervertebral disc and stabilization, and transmission belt.

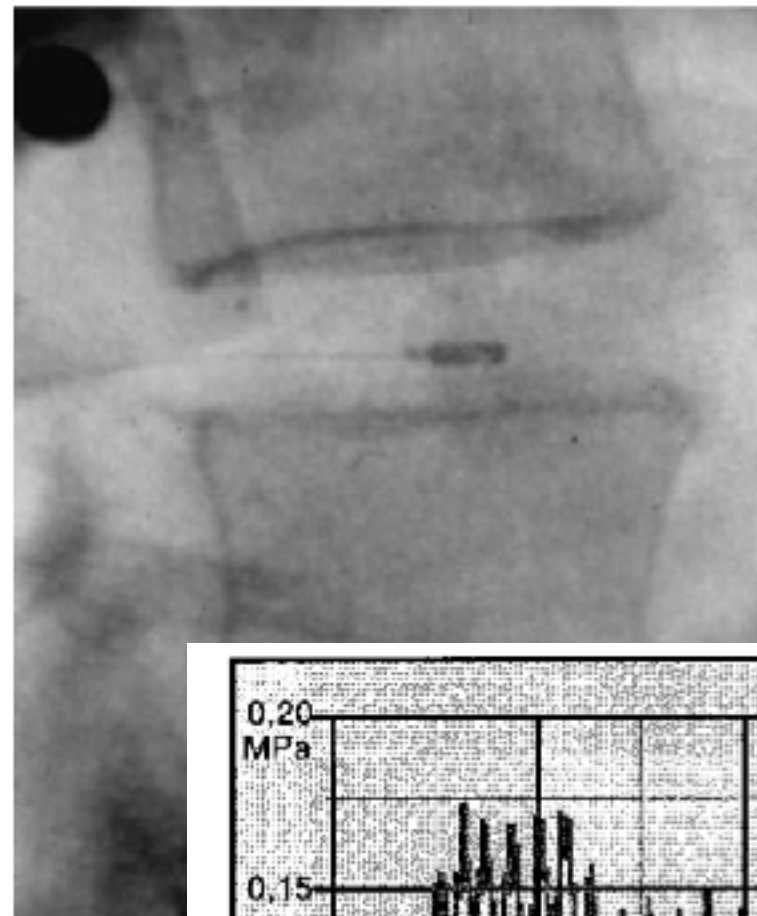
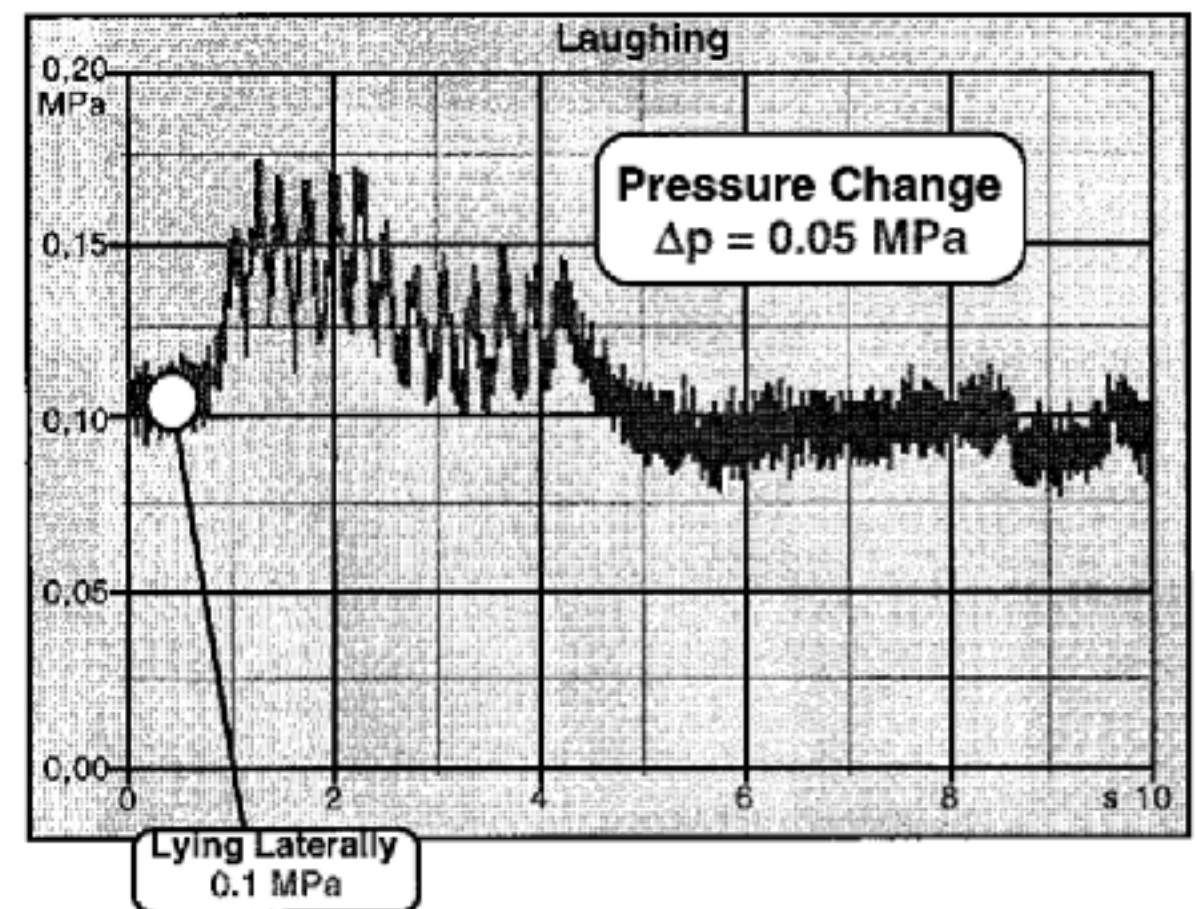


Figure 3. Close-up of the implanted transducer.

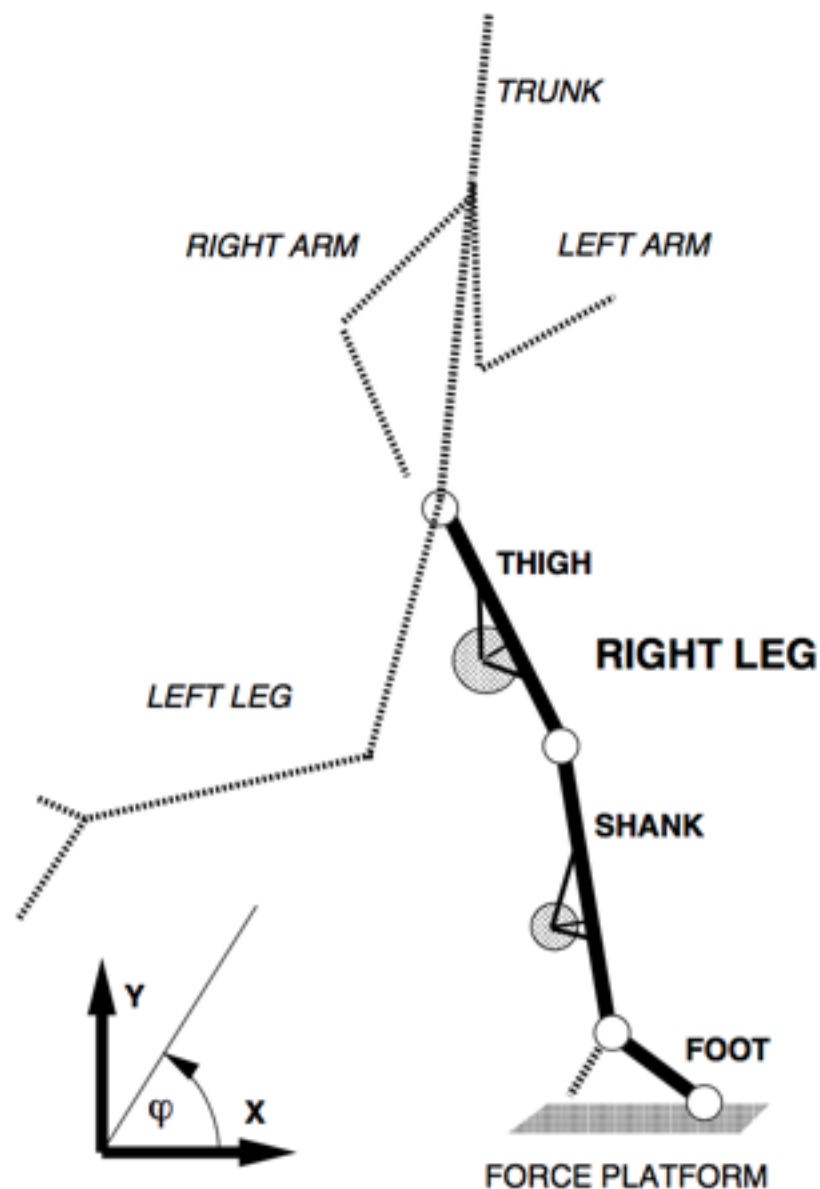


Wilke et al. 1999, New In Vivo Measurements of Pressures in the Intervertebral Disc in Daily Life, SPINE Volume 24, Number 8, pp 755–762

# Force transducers: advantages and disadvantages

---

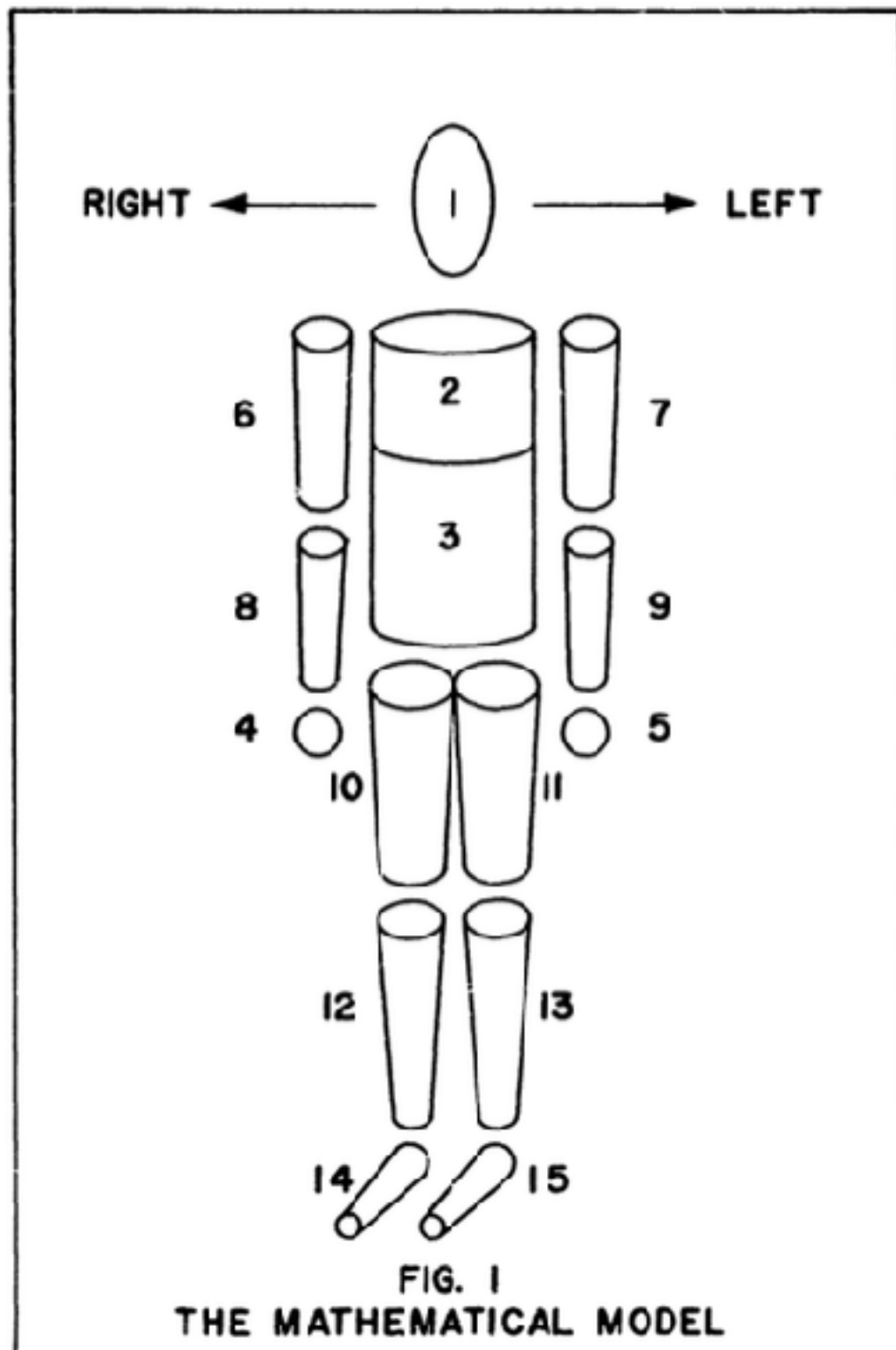
# How to measure force: second approach



$$M_{i+1,i} = \theta_i \ddot{\varphi}_i - M_{i-1,i} - X_{i,i-1} F_{i-1,i/y} + Y_{i,i-1} F_{i-1,i/x} - X_{i,i+1} F_{i+1,i/y} + Y_{i,i+1} F_{i+1,i/x} - \sum_{k=1}^{n_{k(i)}} M_{k,i/coup} (\vec{F}_{k,i/coup}) .$$

Günther, M., Sholukha, V. a., Kessler, D., Wank, V., & Blickhan, R. (2003). Dealing With Skin Motion and Wobbling Masses in Inverse Dynamics. *Journal of Mechanics in Medicine and Biology*, 3(03n04), 309–335. <http://doi.org/10.1142/S0219519403000831>

# How to acquire masses?



Weight of head neck and trunk

$$\text{HNT} = .47 W + 12.0$$

Weight of upper arm

$$\text{BUA} = .08 W - 2.9$$

Weight of forearm

$$\text{BFO} = .04 W - 0.5$$

Weight of hand

$$\text{BH} = .01 W + 0.7$$

Hanavan, E. P. (1964). A mathematical model of the human body. Wright-Patterson Air Force Base, OH.

# How to acquire accelerations?

---



**Figure 1.** Experimental setup. Four force plates in series were embedded in the indoor track. Force plates were covered with the same material (different color) as the entire indoor track. Twelve **Vicon** cameras arranged around the force plates captured the athletes' motions.



Brüggemann, G.-P., Arampatzis, A., Emrich, F., & Potthast, W. (2009). Biomechanics of double transtibial amputee sprinting using dedicated sprinting prostheses. *Sports Technology*, 1(4–5), 220–227. <http://doi.org/10.1002/jst.63>

Haeufle, D. F. B., Worobets, J., Wright, I., Haeufle, J., & Stefanyshyn, D. (2012). Golfers do not respond to changes in shaft mass properties in a mechanically predictable way. *Sports Engineering*, 15(4), 215–220. <http://doi.org/10.1007/s12283-012-0104-9>

# Inverse dynamics: advantages and disadvantages

---

**Problem:**

**How to predict internal  
forces and loads?**

**...predict outcome of  
surgery?**

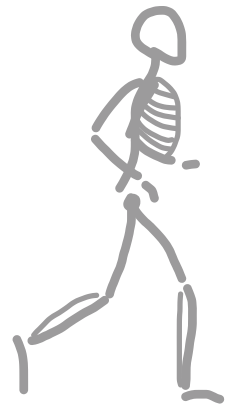
**surgery?**

# What we need:

---

# Structures

---



Bones



Tissue



Muscle

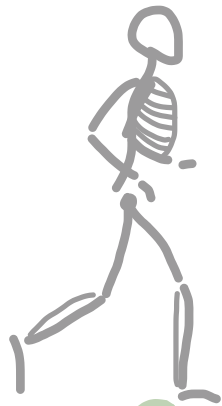


Neurons



# Our viewpoint on natural systems

---



Bones  
Structure

Rigid  
bodies

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{q}_i} - \frac{\partial L}{\partial q_i} = Q_i$$



Ligaments,  
cartilage, fat  
Springs

Passive  
force

$$F_p = f(z, \dot{z})$$

with  $\mathbf{z} = [q_1, \dots, q_n, o_1, \dots, o_m]^T$

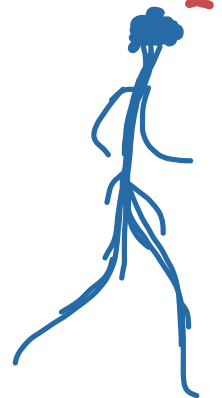


Muscles  
Motors

Active  
force

$$F_a = f(z, \dot{z}, u)$$

with  $\mathbf{u} = [u_1, \dots, u_k]^T$



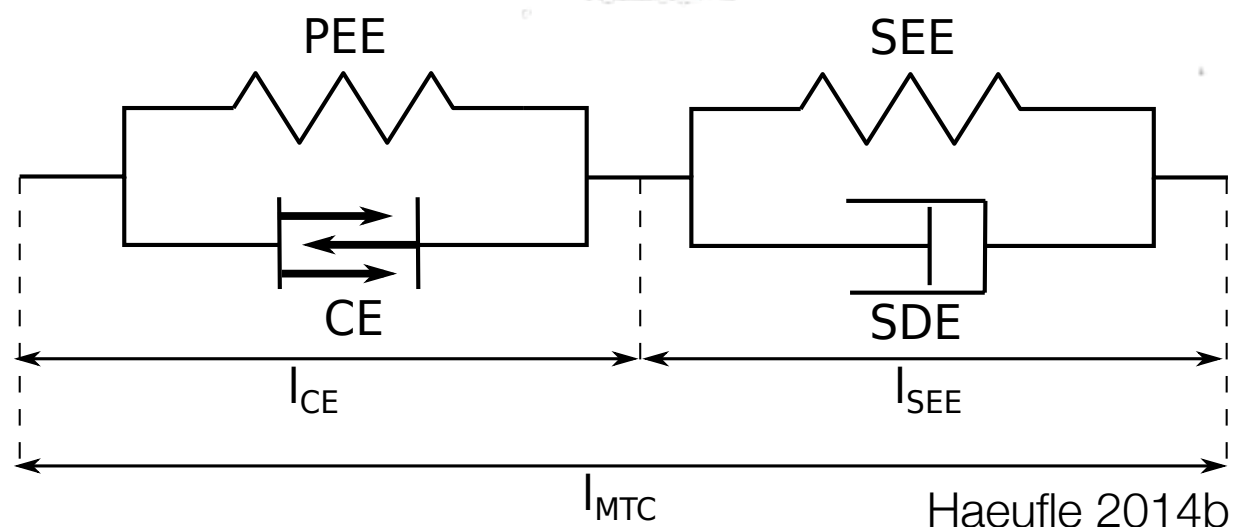
Neurons  
Wires, CPU

Reflexes,  
commands

$$u = f(z, \dot{z}, \text{"brain"})$$



# Structure: muscle



## Biochemistry: activation dynamics

$$\dot{a}_j = f_a(a_j, l_j^{CE}, u_j^{CE})$$

## Biophysics: contraction dynamics

$$\dot{l}_j^{CE} = f_v(l_j^{MTU}, v_j^{MTU}, l_j^{CE}, a_j)$$

$$F_j^{MTU} = f_f(l_j^{MTU}, v_j^{MTU}, l_j^{CE}, a_j)$$



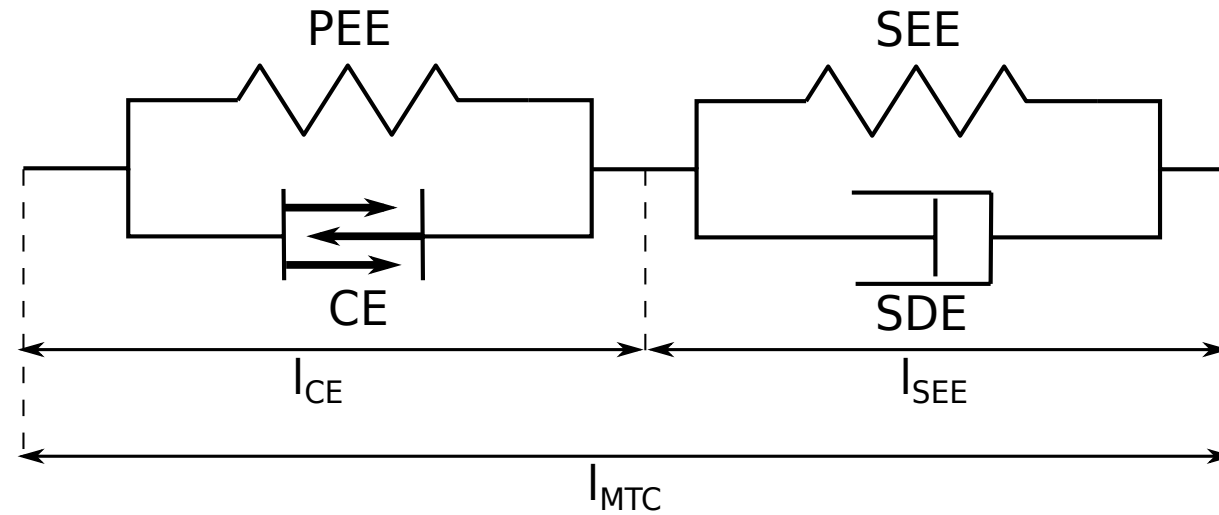
# Structure: muscle

$$F_{PEE}(l_{CE}) = \begin{cases} 0, & l_{CE} < l_{PEE,0} \\ K_{PEE}(l_{CE} - l_{PEE,0})^{\nu_{PEE}}, & l_{CE} \geq l_{PEE,0} \end{cases}$$

$$K_{PEE} = \mathcal{F}_{PEE} \frac{F_{max}}{(l_{CE,opt}(\Delta W_{limb=des} + 1 - \mathcal{L}_{PEE,0}))^{\nu_{PEE}}}$$

$$F_{SEE}(l_{SE}) = \begin{cases} 0, & l_{SE} < l_{SEE,0} \\ K_{SEE,nl}(l_{SE} - l_{SEE,0})^{\nu_{SEE}}, & l_{SE} < l_{SEE,nll} \\ \Delta F_{SEE,0} + K_{SEE,l}(l_{SE} - l_{SEE,nll}), & l_{SE} \geq l_{SEE,nll} \end{cases}$$

$$F_{CE}(l_{CE}, \dot{l}_{CE}, q) + F_{PEE}(l_{CE}) = F_{SEE}(l_{CE}, l_{MTC}) + F_{SDE}(l_{CE}, \dot{l}_{CE}, \dot{l}_{MTC}, q).$$



$$F_{CE,c}(\dot{l}_{CE} \leq 0) = F_{max} \left( \frac{qF_{isom} + A_{rel}}{1 - \frac{\dot{l}_{CE}}{B_{rel}l_{CE,opt}}} - A_{rel} \right).$$

$$F_{SDE}(l_{CE}, \dot{l}_{CE}, \dot{l}_{MTC}, q)$$

$$= D_{SDE,max} \cdot \left( (1 - R_{SDE}) \cdot \frac{F_{CE}(l_{CE}, \dot{l}_{CE}, q) + F_{PEE}(l_{CE})}{F_{max}} + R_{SDE} \right) \cdot (\dot{l}_{MTC} - \dot{l}_{CE})$$

$$F_{isom}(l_{CE}) = \exp \left\{ - \left| \frac{l_{CE}/l_{CE,opt} - 1}{\Delta W_{limb}} \right|^{\nu_{CE,limb}} \right\}$$



# Structure: muscle

$$\dot{l}_{CE} = \dot{l}_{CE}(l_{CE}, l_{MTC}, \dot{l}_{MTC}, q).$$

$$\dot{l}_{CE} = \begin{cases} \frac{-C_1 - \sqrt{C_1^2 - 4 \cdot C_2 \cdot C_0}}{2 \cdot C_2}, & \dot{l}_{CE} \leq 0 \\ \frac{-C_{1,e} + \sqrt{C_{1,e}^2 - 4 \cdot C_{2,e} \cdot C_{0,e}}}{2 \cdot C_{2,e}}, & \dot{l}_{CE} > 0 \end{cases}$$

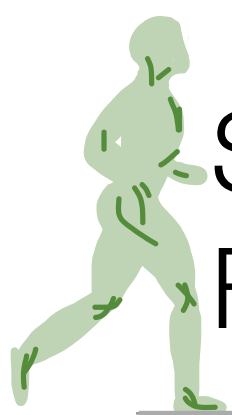
$$C_2 = d_{SE,max}(l_{CE}, q) \cdot \left( R_{SE} - \left( A_{rel}(l_{CE}, q) - \frac{F_{PEE}(l_{CE})}{F_{max}} \right) \cdot (1 - R_{SE}) \right)$$

$$C_1 = -(C_2 \cdot \dot{l}_{MTC} + D_0 + F_{SEE}(l_{MTC}, l_{CE}) - F_{PEE}(l_{CE}) + F_{max} \cdot A_{rel}(l_{CE}, q))$$

$$C_0 = D_0 \cdot \dot{l}_{MTC} + l_{CE,opt} \cdot B_{rel}(l_{CE}, q) \cdot (F_{SEE}(l_{MTC}, l_{CE}) - F_{PEE}(l_{CE}) - F_{max} \cdot q \cdot F_{isom}(l_{CE}))$$

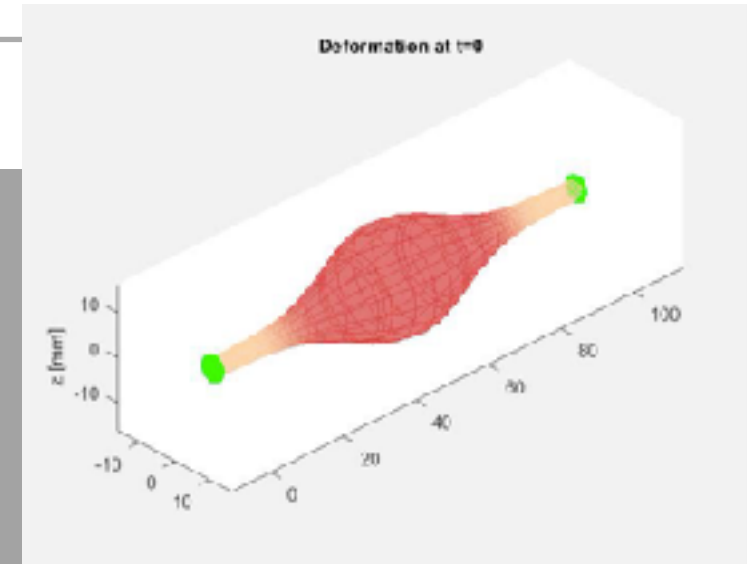
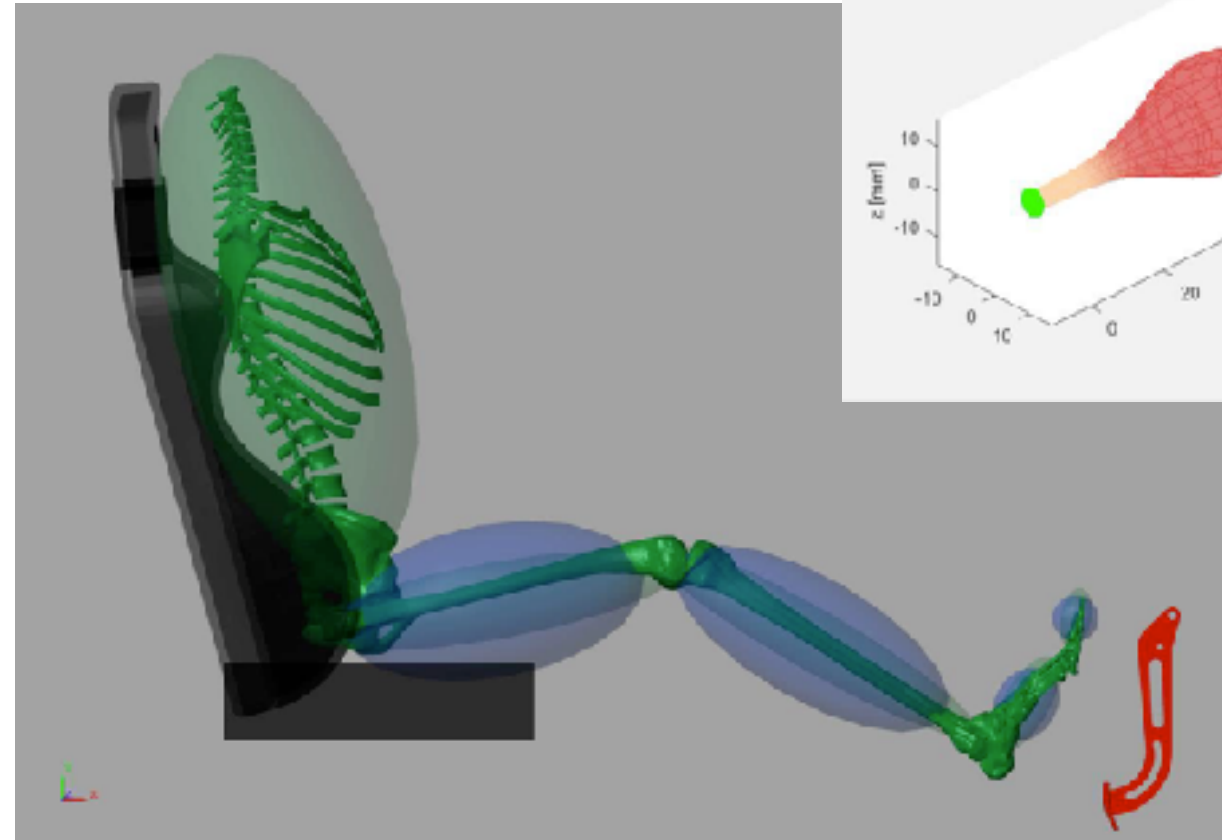
(17)

$$D_0 = l_{CE,opt} \cdot B_{rel}(l_{CE}, q) \cdot d_{SE,max}(l_{CE}, q) \cdot \left( R_{SE} + (1 - R_{SE}) \cdot \left( q \cdot F_{isom}(l_{CE}) + \frac{F_{PEE}(l_{CE})}{F_{max}} \right) \right)$$



Structure: soft tissue

Function: interaction with the environment

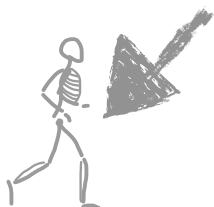


Schmitt 2014

$$\vec{F}_{k,i/coup} = \left( C_{k,i} |\vec{d}|^{eC_{k,i}} + D_{k,i} \frac{\dot{\vec{d}} \vec{e}_d}{|\dot{\vec{d}} \vec{e}_d|^{eD_{k,i}}} \right) \vec{e}_d,$$

Günther et al. 2003

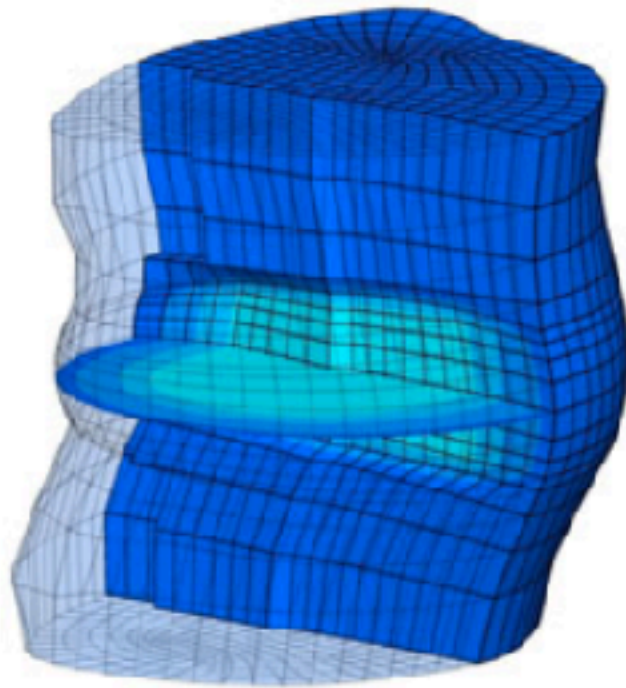
continuum-mechanics  
mass distribution



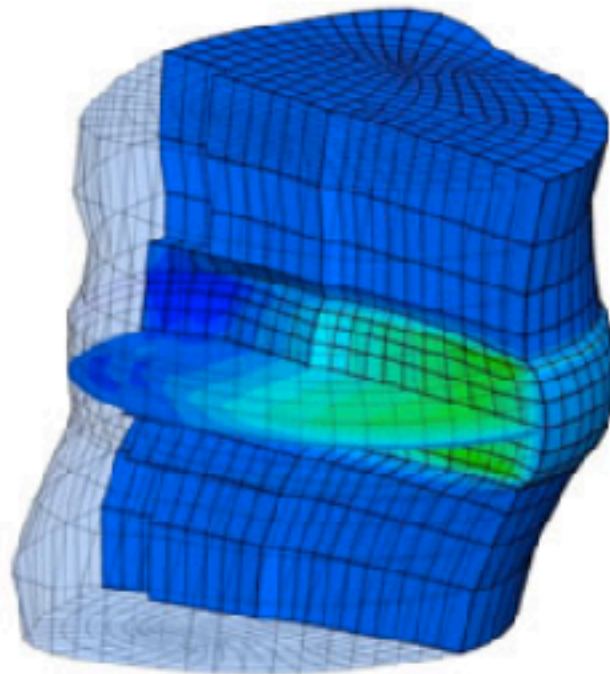


Structure: soft tissue

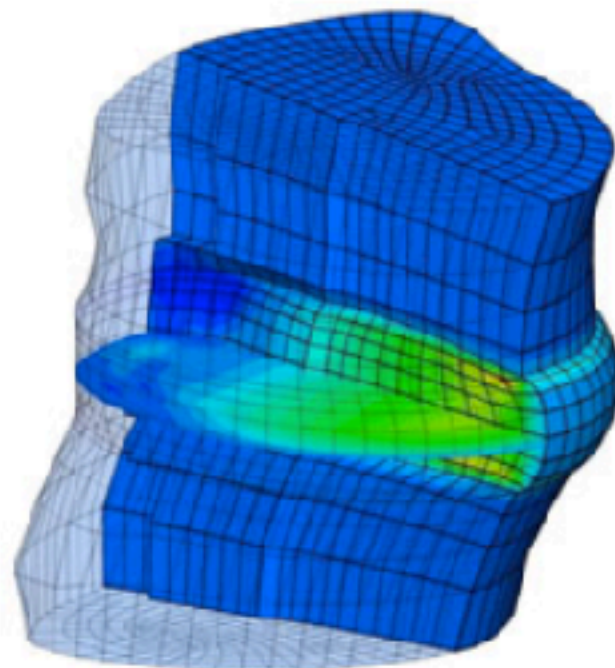
Function: relative movement and absorbing energy



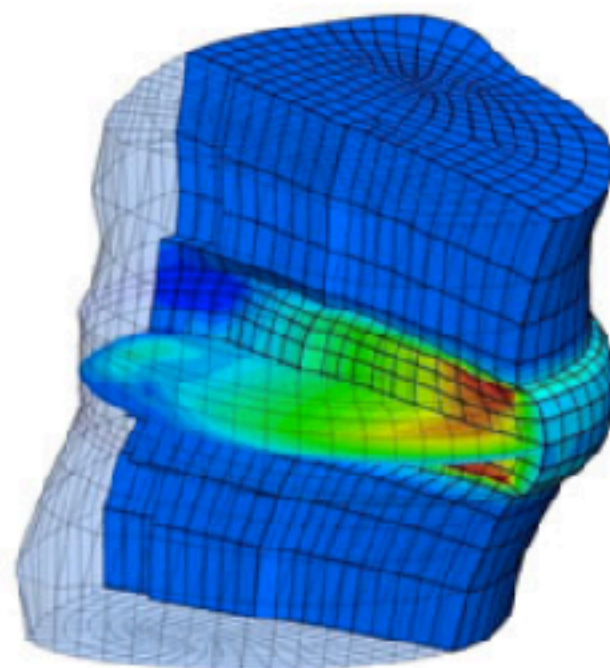
(a)  $t = 0 \text{ s}$



(b)  $t = 0.33 \text{ s}$



(c)  $t = 0.66 \text{ s}$



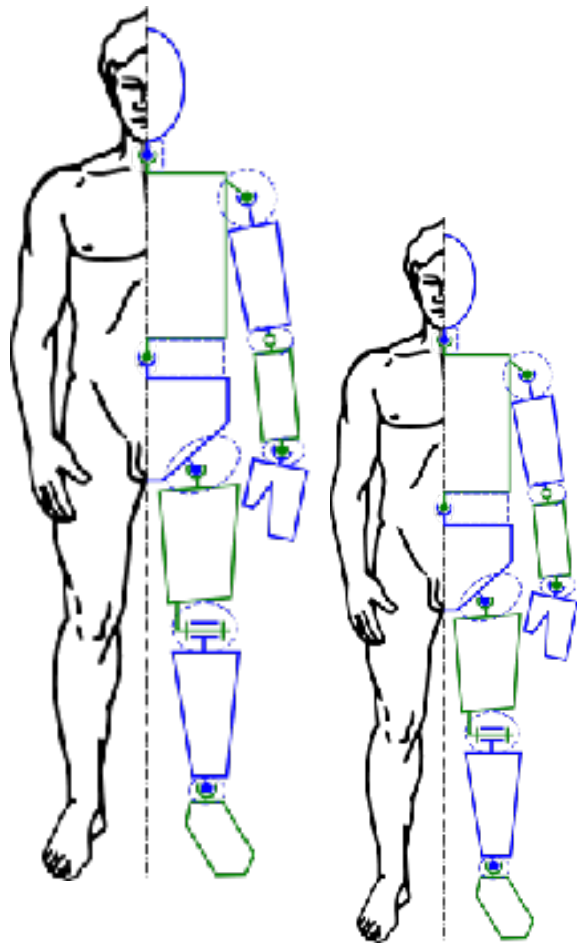
(d)  $t = 1.0 \text{ s}$

Karajan, N. (2012). Multiphasic Intervertebral Disc Mechanics: Theory and Application. Archives of Computational Methods in Engineering, 19(2), 261–339. <http://doi.org/10.1007/s11831-012-9073-1>



Structure: bones and joints

Function: dynamics of the movement





$$\ddot{\underline{q}} = M(\underline{q})^{-1} \left( \underline{f} - C(\underline{q}, \dot{\underline{q}}) - G(\underline{q}) \right)$$

based on Pandy, 2001

$$\begin{aligned} \underline{f} &= \underline{f}^{\text{ext}} + \underline{f}^{\text{active}} + \underline{f}^{\text{passive}} \\ &= \underline{E}(\underline{q}, \dot{\underline{q}}) + R^{\text{act}}(\underline{q}) \underline{F}^{\text{act}}(\underline{q}, \dot{\underline{q}}, u) + R^{\text{pass}}(\underline{q}) \underline{F}^{\text{pass}}(\underline{q}, \dot{\underline{q}}) \end{aligned}$$



Simulation: Demoa  
Anthropometry: CalcMan



Structure: neurons

Function: perception and action

## low-level control


$$u_i = u_i^{\text{open}} + u_i^{\text{closed}} = u_i^{\text{open}} + \left( k_p \cdot \frac{(\lambda_i - l_i^{\text{CE}})}{l_i^{\text{CE,opt}}} \right)$$

Bayer et al. 2016

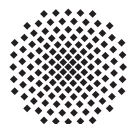
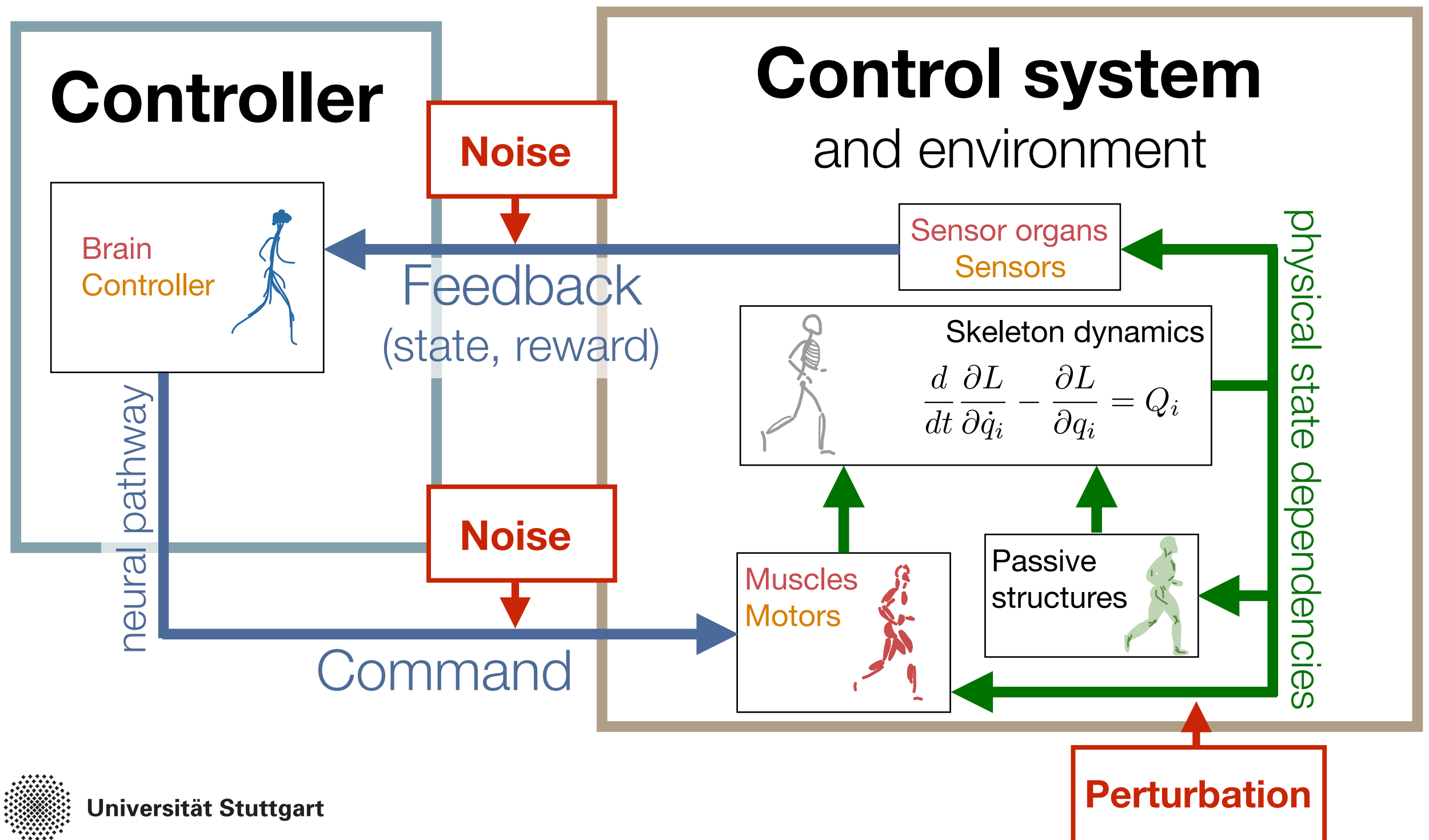
## Computational motor control

- mono-synaptic reflexes
- proprioceptive feedback
- central pattern generators


$$u_i = (w - 1)GF^M(t - \delta) + w \cdot u^{CPG}(t)$$

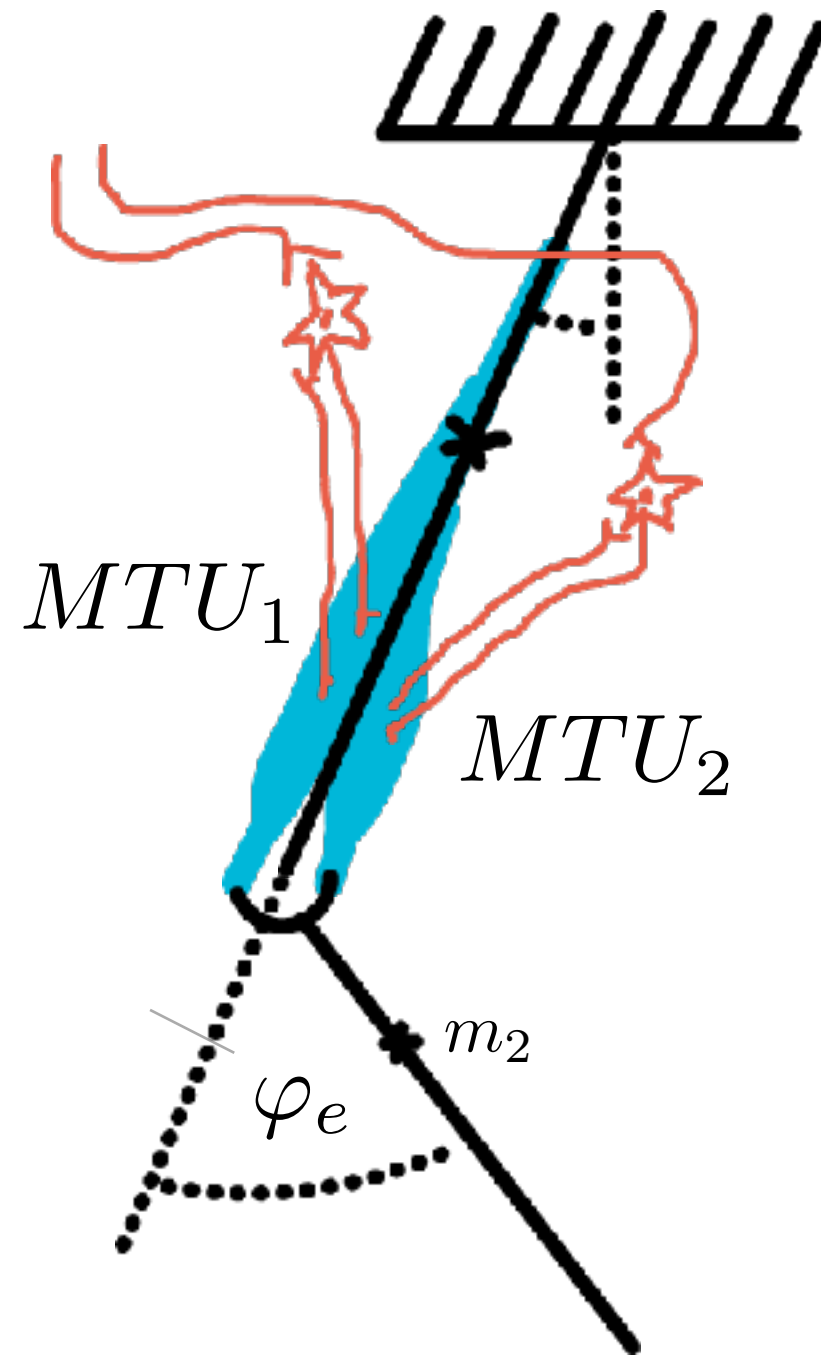
Häufle et al. 2012b, 2016

# Interaction of the structures



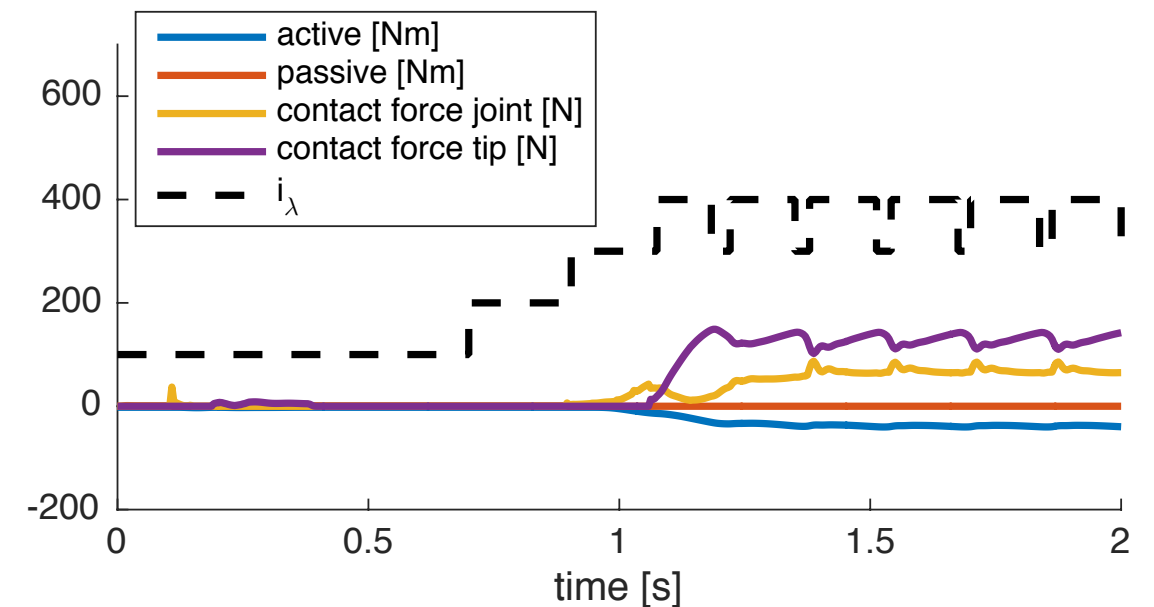
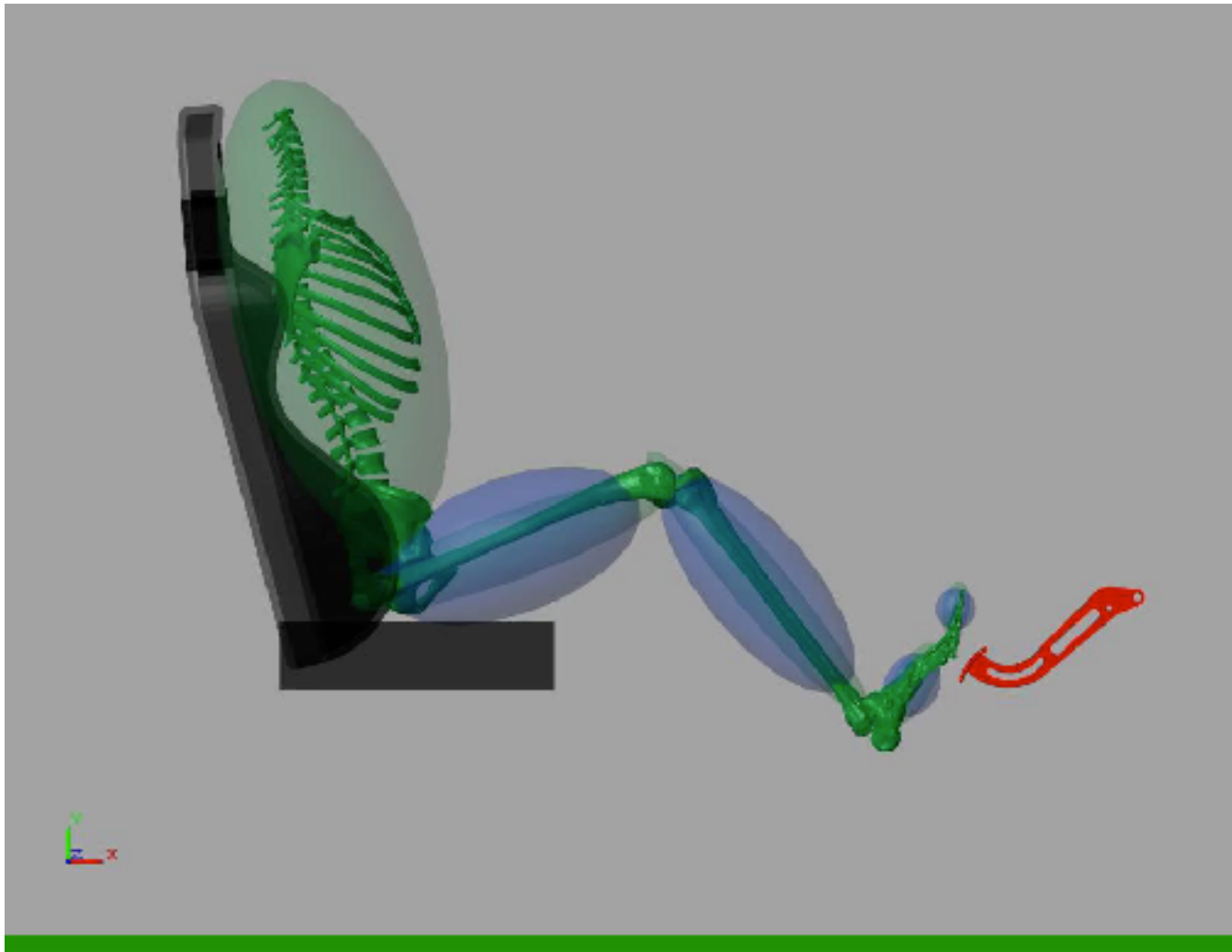
# Predicting muscle forces and joint loading

---



# Predict internal and external forces in a car, which has not been built yet

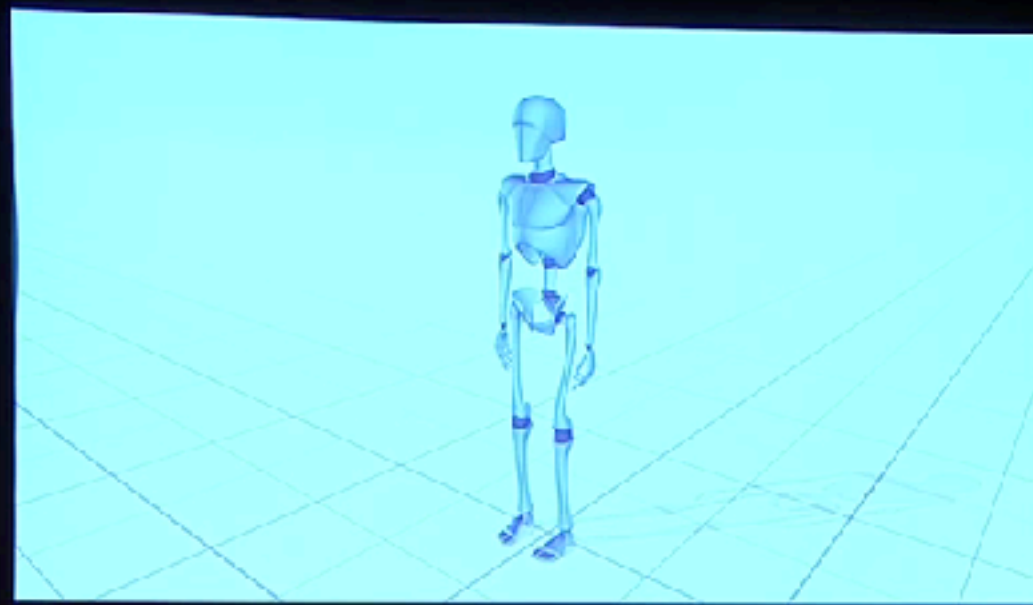
---



Cannot be measured with force transducers,  
cannot be analysed with inverse dynamics.

# Forward dynamics computer simulation: advantages and disadvantages

---



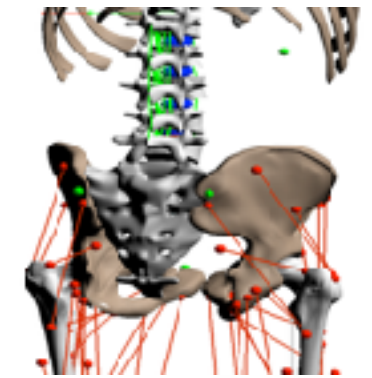
TEDx

***Our most advanced human body model***

# Human model - lower extremity and spine



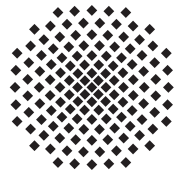
|            |                                   |
|------------|-----------------------------------|
| <b>13</b>  | body segments                     |
| <b>452</b> | degrees of freedom (DOFs)         |
| <b>48</b>  | mechanical DOFs                   |
| <b>202</b> | <b>muscle-tendon-complexes</b>    |
| <b>58</b>  | non-linear ligaments              |
| <b>5</b>   | <b>IVDs (non-linear, coupled)</b> |



|                         |                                                                                      |
|-------------------------|--------------------------------------------------------------------------------------|
| <b>skeletal anatomy</b> | male, 68kg, 1,78m (NASA, 1978)                                                       |
| <b>ligaments</b>        | anatomy (Panjabi, 1982),<br>physiology (Chazal, 1985)                                |
| <b>muscles</b>          | anatomy and physiology (Bogduk,<br>1992a,b, 1998; Hansen, 2006;<br>Christophy, 2012) |
| <b>IVDs</b>             | multi-scale model (Karajan, Röhrle, Ehlers<br>& Schmitt, 2012)                       |



***Vibration analysis of lumbar spine loading -  
influence of two different muscle activity levels***



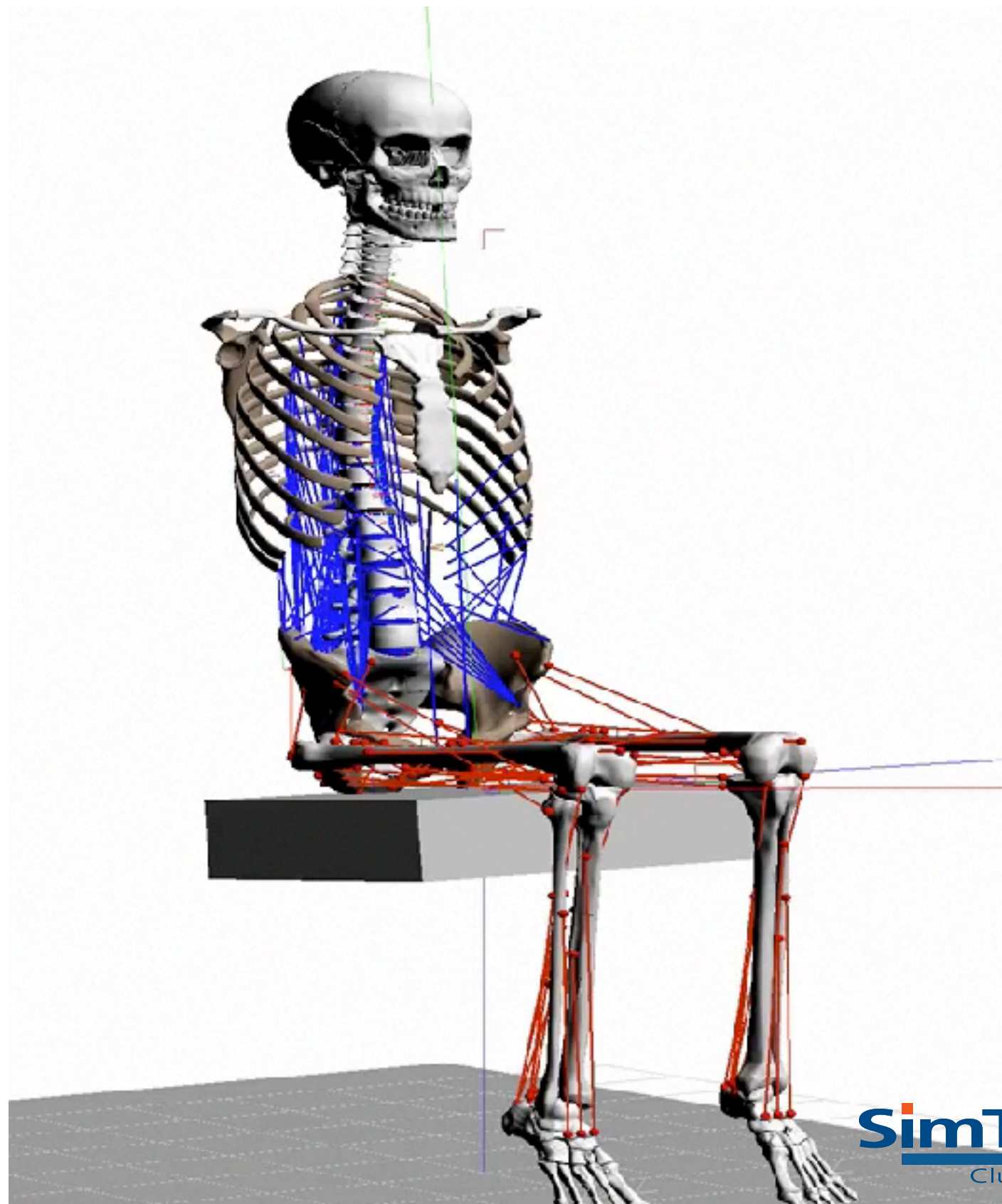
Universität Stuttgart

**seated vibration**  
at 15Hz, 5mm

**two models**

(1) passive trunk  
muscles,  
(2) active trunk  
muscles

**dynamic peak  
loads** on ivds  
are reduced  
up to 30%



**SimTech**  
Cluster of Excellence

Bayer et al. (2016) submitted

***A numerical application in spinal fusion surgery***

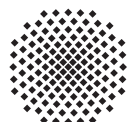
# Spinal fusion surgery

... number of spinal-fusion surgery... is rapidly increasing.  
(Deyo et al., 2004)

Adjacent segment degeneration and adjacent segment disease: the consequences of spinal fusion?  
(Hilibrand & Robbins, 2004)

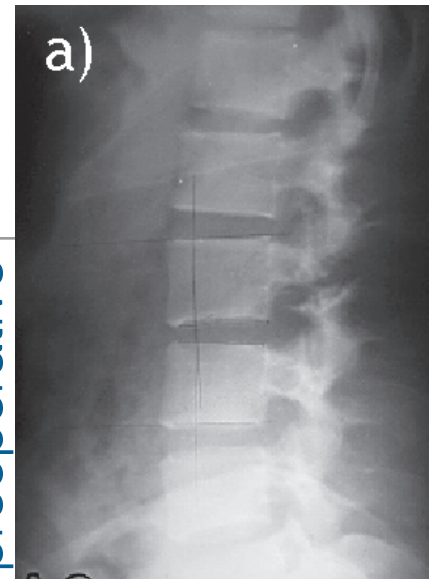


**Change of ...  
...displacement, internal  
forces and moments?**

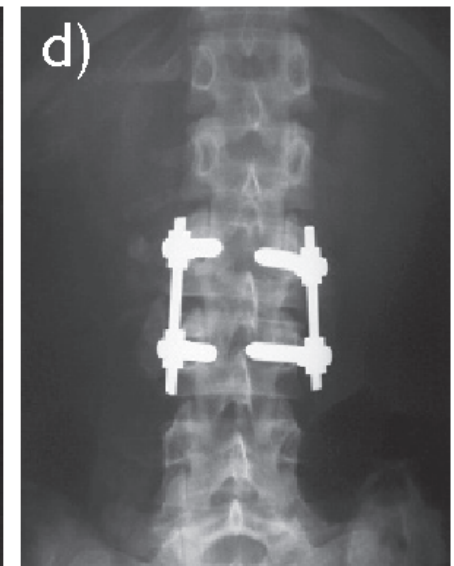
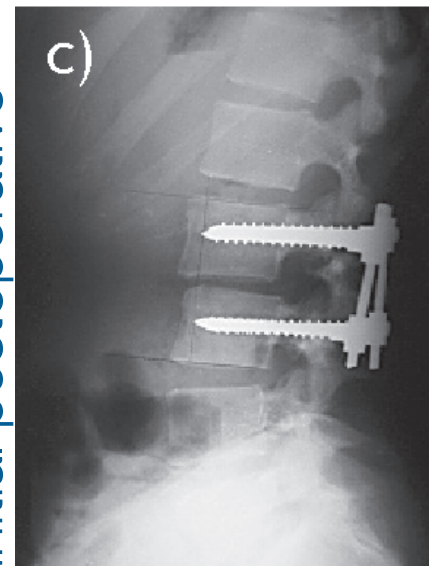


Universität Stuttgart

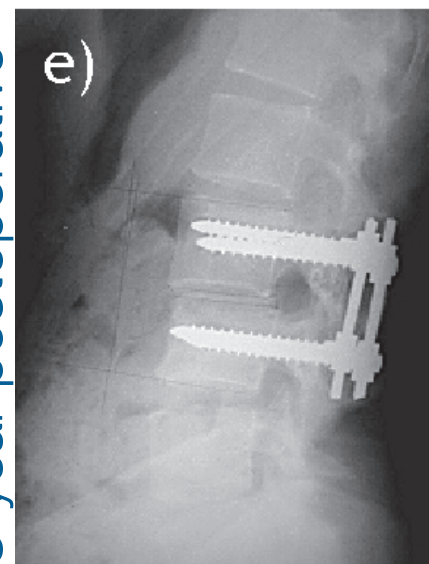
preoperative



initial postoperative



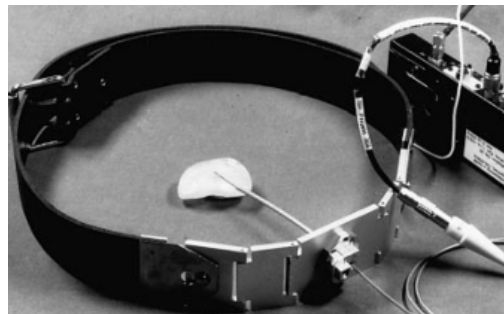
8-year postoperative



(Defino & Scarparo, 2005)

# Take home:

- Knowing about internal dynamics, loads and forces is important

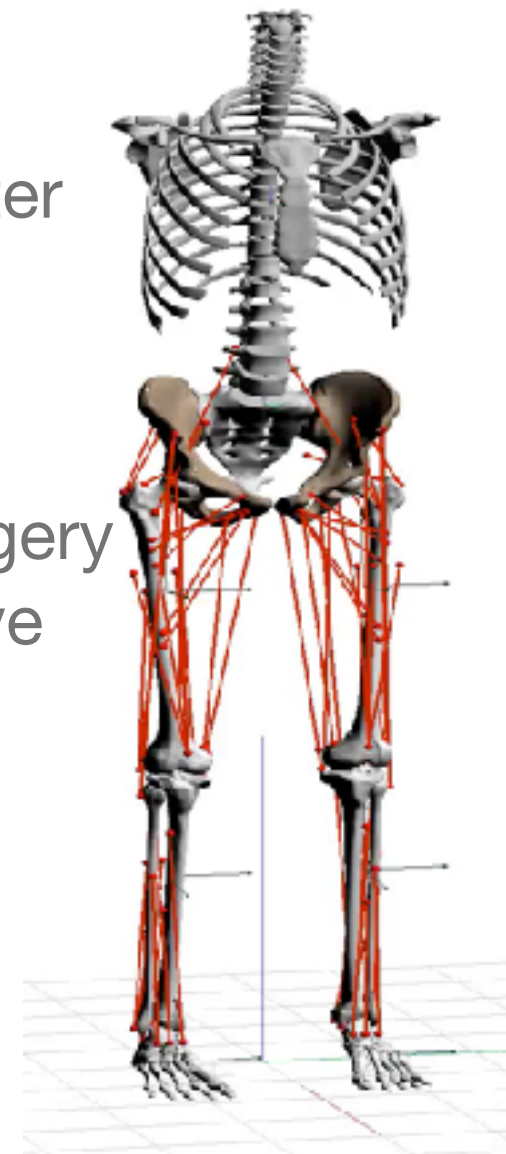


- Measure forces:
  - + direct results
  - invasive
  - analysis tool

- Inverse dynamics
  - + robust
  - + clinical acceptance
  - only net joint torques
  - analysis tool



- Forward dynamics computer simulation
  - + synthesis tool
  - + predicts outcome
  - + may be used to plan surgery
  - computationally expensive
  - difficult to model



# Homework

---

## Spine Exoskeleton

Weston, E. B., Alizadeh, M., Knapik, G. G., Wang, X., and Marras, W. S. (2018). Biomechanical evaluation of exoskeleton use on loading of the lumbar spine. *Appl. Ergon.* 68, 101–108. doi:10.1016/j.apergo.2017.11.006.

## Knee prosthesis

Pauline Gerus, Massimo Sartori, Thor F. Besier, Benjamin J. Fregly, Scott L. Delp, Scott A. Banks, Marcus G. Pandy, Darryl D. D'Lima, David G. Lloyd, (2013) Subject-specific knee joint geometry improves predictions of medial tibiofemoral contact forces, *Journal of Biomechanics*, 46(16), 2778-2786, doi:10.1016/j.jbiomech.2013.09.005.

Install Matlab Simulink from ZDV

Try command: smnew (if it does not work install required toolboxes)

Download test model (will be uploaded in time)